Experimental Evaluation of White Light Fabry-Perót Interferometry Fiber-Optic Strain Gages when Measuring Small Strains

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Abstract

An experimental study was conducted to evaluate whether fiber optic strain gages (FOSG) are "better" sensors than typical foil gages. A particularly attractive feature of FOSG was their specified resolution of 0.01% of full-scale (0.1 μstrain for 1000 μstrain full-scale). This feature would make FOSG practical tank level sensors, by measuring very small strains on the support structure of a tank. A specific application in mind was to measure liquid oxygen tank level, with support beams that were predicted to contract approximately 11 μstrain as the tank goes from empty to full. Among various fiber optic technologies currently available, Fabry-Perót Interferometry using white light was selected. This technology exhibits highly desirable features such as absolute strain measurement, linearity over its full-scale, and temperature compensation. However, experimental results suggest that the resolution is 0.8 μstrain, at best, calibration from one sensor to another can be off by 2.4-11.2%, and that temperature compensation is not fully predictable, with errors of up to 3.5 μstrain over an 11°C range. Hence, when compared with classic foil gages, FOSG possess less accuracy, similar resolution and repeatability (precision), and superior linearity over their entire operating range. They are immune to EMI and their signals suffer minimal degradation over long distances. It is also expected that drift with time will be minimal in FOSG whereas the gage factor of foil sensors changes over time when exposed to varying environmental conditions. In conclusion, FOSG are "better" than foil gages as long as the application allows calibration of individual units as installed for operation.

Background

Although much has been done to apply fiber optic technology to design a variety of sensors, few are truly commercially available. Classical temperature, pressure, and strain sensors have not been displaced by this new technology to any significant extent. There could be important advantages to using fiber optic (FO) sensors over resistance, piezoelectric, or thermoelectric sensors, but these cannot be realized until FO sensors are proven to be "better" than classical sensors. A series of experiments were carried out to evaluate the performance of FOSG against classic foil strain gages, focusing on accuracy, resolution, precision, drift, and temperature compensation.

Foil Gages are widely used to measure strain. They are small, and have gained wide acceptability across the scientific and engineering community. However, they have a number of shortcomings that FO sensor technology overcomes. A brief discussion follows.

- Change in resistance of the strain gage not caused by an applied stress to the material where the gage is bonded causes an apparent strain. This is due to a differential in thermal expansion between the gage and the specimen. To mitigate this problem, the thermal expansion coefficient of the gage and material must be the same. Metallurgical processing has provided self-temperature compensating gages to minimize these errors. FOSG are only sensitive to strain (deformation) and not the onset of stress without deformation.

- Apparent strains occur due to temperature sensitivity of the foil's resistance element (caused also by heating from the excitation current). Using a reference gage subjected only to temperature changes mitigates this problem. FOSG do not have self-heating elements.
- Noise due to use of long leads enhances electromagnetic interference (EMI) and degrades signal quality. This is mitigated by use of shielded wires. FOSG are immune to EMI.
- Long leads have significant resistance/capacitance that produces loading on the strain gage measurement system. Using a third or fourth wire as compensation leads mitigates this problem. Fiber optic cables do not experience this problem.
- Foil gages have non-linear temperature characteristics. Compensation requires the use of additional reference units if operating conditions involve large temperature excursions. FOSG are linear and compensation is predictable and maybe done analytically, without a reference unit.

Additional advantages of FOSG include corrosion resistance and practically zero probability to generate sparks. These are very attractive attributes for many applications at Stennis Space Center.

Operation of White Light Fabry-Peròt Fiber Optic Strain Gages (FPFOSG)

These sensors consist of a multimode optical fiber used to transport white light, with the sensing element at the tip. The sensing element is defined by a micro capillary tube that holds the end of the fiber close to another small piece of the same fiber, leaving a cavity in between [1-3](Figure 1). The fiber-ends that define the cavity are deposited with mirrors, so that the white light entering the cavity is reflected, and hence frequency-modulated in accordance to this length. When the sensor is bonded to a surface, the length of the cavity in the micro capillary expands or contracts exactly by the same amount of strain experienced by the surface ($Strain = \frac{\Delta L_{Cavity}}{L_{Gauge}}$).

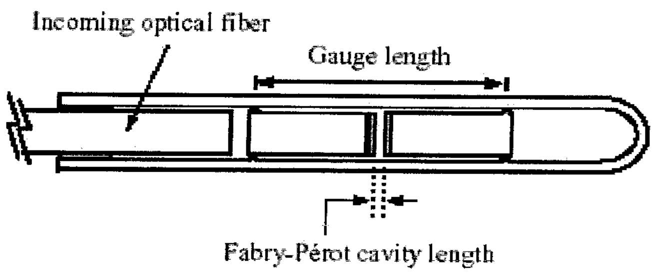

Figure 1 Fabry-Perot FOSG: Schematic (Courtesy of FISO Technologies, Inc. [7])

The modulated light returning from the sensing element is interpreted using a white light cross-correlator. This device matches the sensor's cavity-length to the thickness of a specific location in the variable-thickness lens [3](Figure 2 and Figure 3). The light transmitted through this specific location in the lens contains the highest level of energy as a result of modulation in the sensor cavity. The light is detected by a CCD array, where the pixel receiving the highest amount of energy corresponds to the sensor cavity-length. Each pixel of the array corresponds to a specific cavity length.

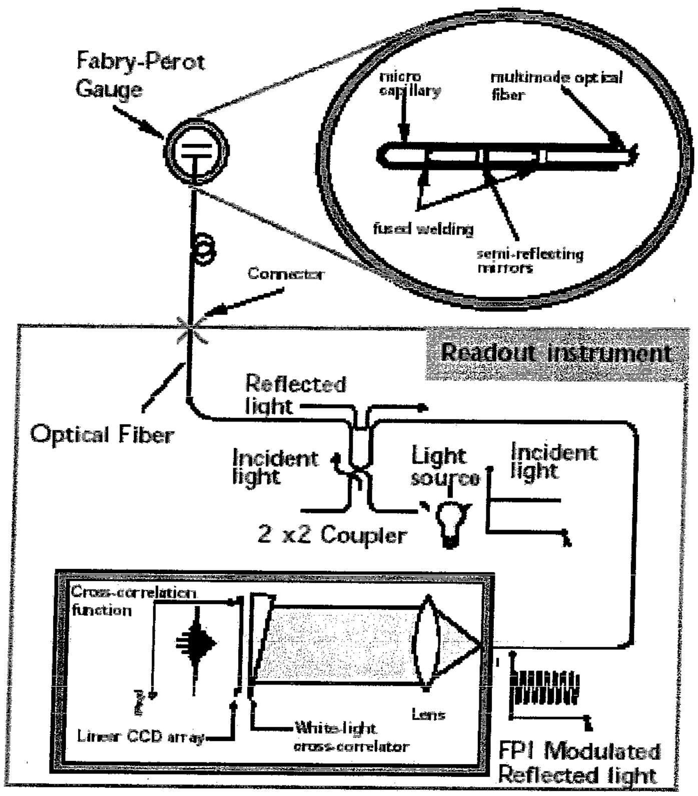

Figure 2. FOSG Signal Conditioning Components (Courtesy of FISO Technologies, Inc. [7])

Temperature compensated FOSG are also available. These units null-out strain on the measurand due solely to temperature variations. Compensation is accomplished by the use of a metallic fiber with the same thermal coefficient of expansion as that of the material being measured (Figure 4).

White-light Fabry-Perót interferometry fiber-optic strain-gages are robust, exhibiting a design that leaves little room for variation/degradation in performance. Measurement of the cavity length is encoded by light-frequency rather than amplitude, thus significant variations in performance by the light sources do not affect the sensor's performance.

Other Fabry-Perót Interferometric Sensors

Other sensors using Fabry-Perót Interferometry have been developed, with the difference that they use single-mode fiber [4]. In general, processing of the modulated light tends to be more complex for these signals, but commercial units were found to have comparable performance to the sensors tested by us (sensors that use white-light sources). Researchers at NASA Langley Research Center tested fiber optic sensors [5], but they did not focus on small levels of strain, as is the case in our study. These sensors also are more costly than the white-light sensors we tested.

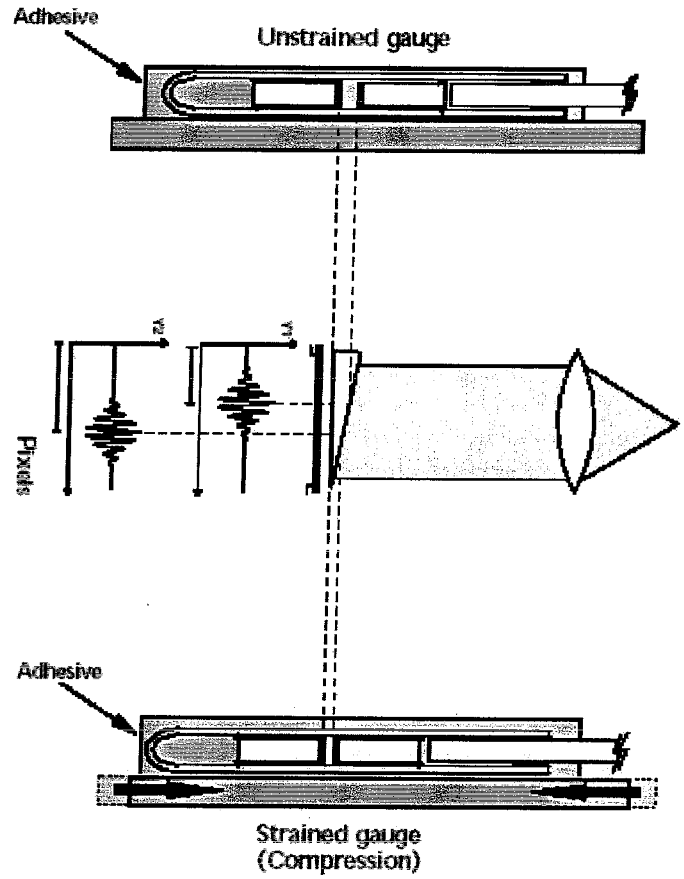

Figure 3. FOSG Cross-Correlator to extract cavity length (Courtesy of FISO Technologies, Inc. [7])

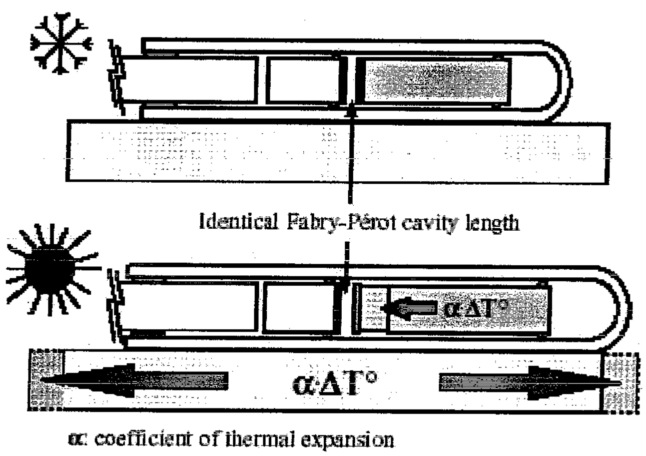

Figure 4. Cross-correlator to extract cavity length measurement (Courtesy of FISO Technologies, Inc. [7])

Test Setup

Two carbon-steel test-beams were prepared for tests. The first beam (Beam 1) was instrumented with two FOSG, one non-compensated and one compensated, one foil gage, and one Type K thermocouple. The uncompensated FOSG, was faulty, and so data was not collected from it. The FOSG and foil gage were mounted in accordance to instructions from the manufacturers. In fact, the procedures are very similar, and the cleaning and bonding materials used are the same. The second beam (Beam2) was instrumented with two FOSG (compensated), two foil gages, and one RTD sensor to measure temperature. In addition, a Reference Beam (small piece of the same material as the beams) was instrumented with one FOSG, one foil gage, and one RTD. The reference beam was subjected to the same temperature conditions as Beam 2, but did not experience stress, thus providing data necessary to compensate experimentally sensor-measurements in Beam 2.

Carbon steel beams were used to match the material of the structure supporting the LOX tank of interest. The compensated FOSG were specified to match the thermal expansion coefficient of carbon steel (12 μstrain/°C). Beam 1 was 2.5 in x 13 in x 0.1in, mounted so that the cantilevered portion would measure 12 in. Beam 2 was similar, except for the thickness, which was increased to 0.128 in.

A thermocouple was used with Beam 1, but to improve accuracy, RTDs were used with Beam 2 and the Reference Beam.

Figure 5 shows Beam 2, and Figure 6 shows the experimental setup. A FOSG bus-unit and individual conditioning modules were used for the FOSG (Bus-System Fiber Optic Signal Conditioner, FISO Technologies, Ste-Foy Quebec - Canada). Analog signals from each conditioning unit were sampled using National Instruments' SCXI 1100 Module (32-channel Analog Input Module), filtered at 4 Hz. Foil gage signals were conditioned and sampled using National Instruments' SCXI 1520 Module (Universal Strain Gage Input Module), filtered at 10 Hz. All data was sampled at 100 samples/second.

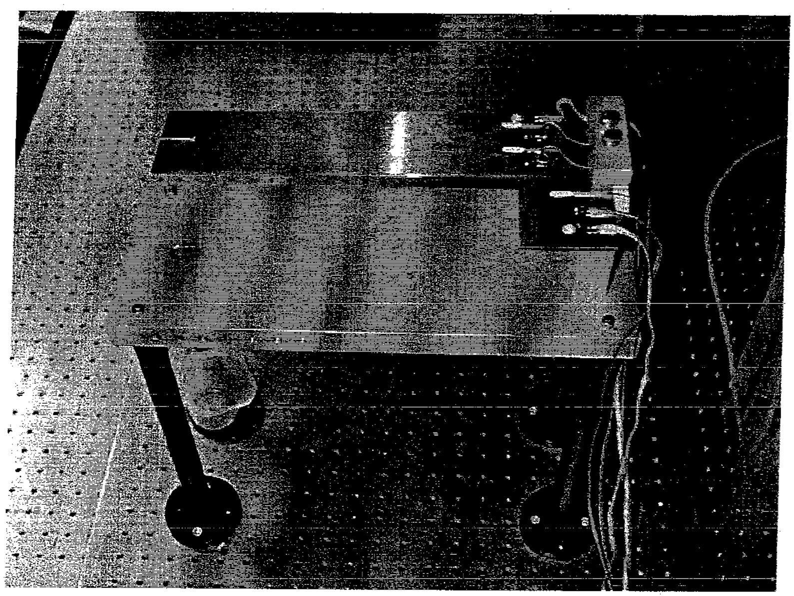

Figure 5. Beam 2 (2 FOSG, 2 foil gages, and 1 RTD) and Reference Beam (1 FOSG, 1 foil gage, and 1 RTD).

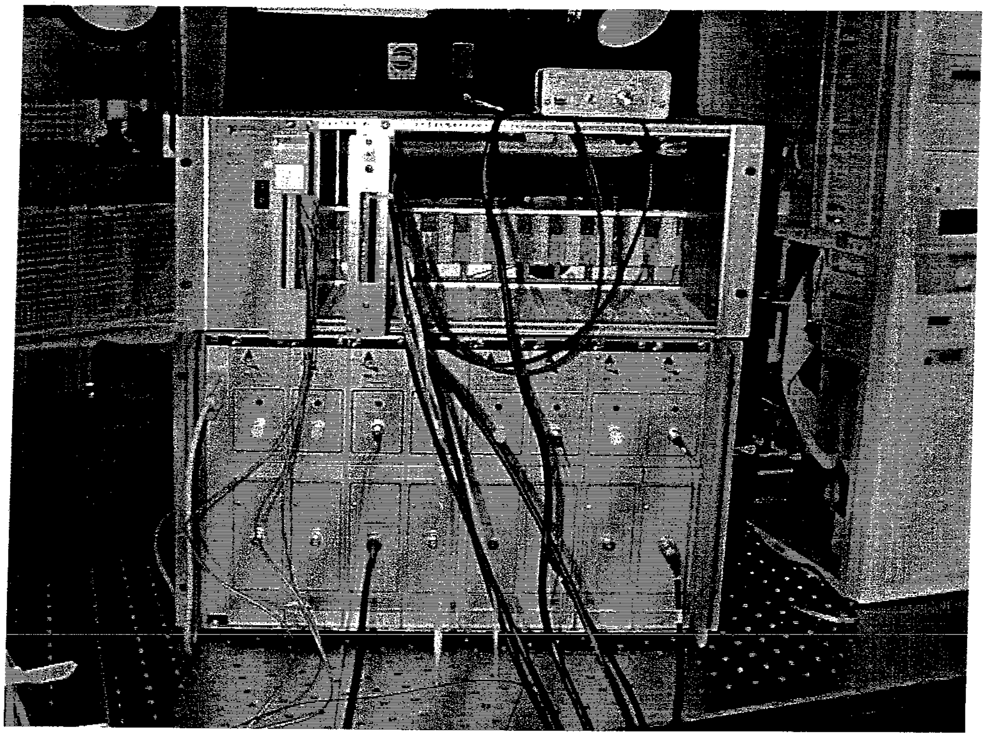

Figure 6. Experiment Instrumentation: FOSG conditioning rack and modules (below), rack and conditioning modules for foil strain gages (above), and current source for RTD's (on top)

Temperature experiments were done using a variable transformer (VARIAC) to control the intensity of a light source from 0% to 100% of its rated wattage (60 watts). To reach and maintain stable environmental conditions, the beams were placed inside an enclosure.

A computer program written in LabView [6] was developed to integrate and automate data acquisition. This task represented a significant challenge, since it involved programming a newly developed strain-gage signal-conditioning module, a multi-channel signal conditioning module, and a multi-function data acquisition board mounted inside a personal computer. In addition, the program had to support unattended data acquisition at programmable time intervals and storage of each set of data in files with self-generated names.

Test Procedures and Results

All sensors and instrumentation were kept ON for a warm-up period longer than that prescribed by the manufacturers. Experiments to determine linearity, resolution, and precision, were done using a set of weights that were hung at the end of the beam. Applicable elements of ASTM E 251 – 92 Test Standard Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages were considered in the design and performance of the experiments. For the temperature experiments, a period of 2 hours was determined to be more than sufficient to allow stabilization of the temperature throughout the beam every time the level of intensity of the heat lamp was changed.

Experiments with Beam 1 show that FOSG have very good Linearity (Figure 7). Standard deviations are on the order of 0.04 μstrain for the foil gage and 0.15 μstrain for the FOSG. Errors were determined with respect to theoretical calculations. For the FOSG, the theoretical strain value is larger, because the diameter of the sensor had to be considered (250 microns). The FOSG error is -5.1%, and the Foil error -2.7%. Two consecutive experiments, where the temperature varied minimally (less than 0.14°C), were compared to assess precision. The foil sensors achieve 0.2 μstrain precision and the FOSG 0.06 μstrain precision (Figure 8).

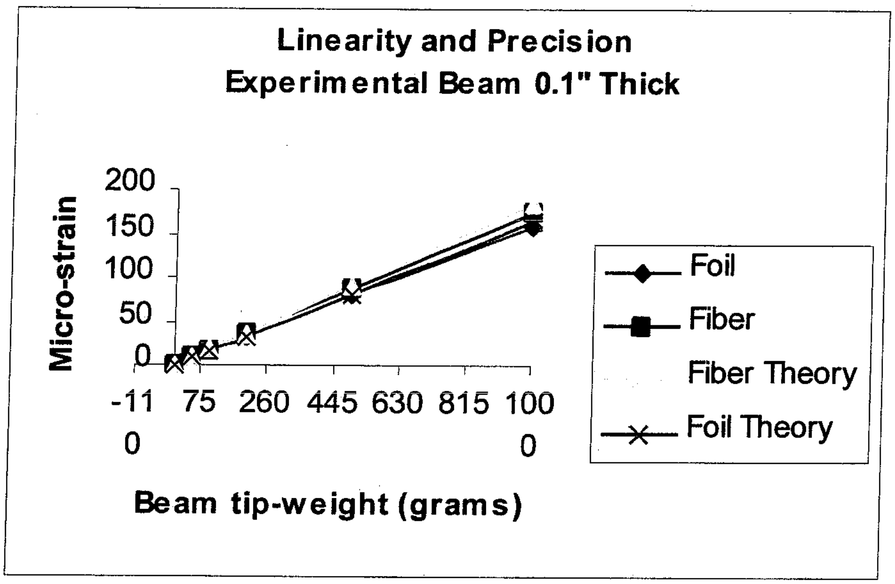

Figure 7. Linearity Experiment with Beam 1.

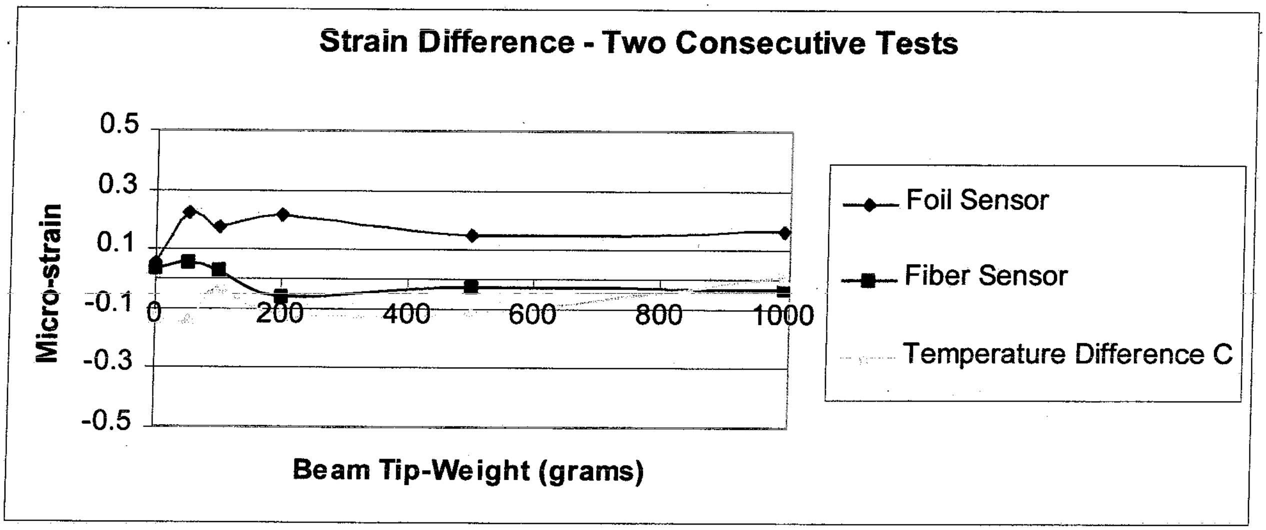

Figure 8 Comparison of two consecutive tests with Beam 1.

An experiment to determine resolution shows that both sensors can resolve about 0.8 μstrain at best (1 μstrain for practical purposes). Figure 9 illustrates the effect of adding small increments of strain (approximately from 0.2 to 3.3 μstrain) at various levels of total strain (approximately from 0 to 180 μstrain). Values are compared with theoretical predictions, which do not consider the diameter of the FOSG, hence they are shown only as a reference.

An experiment to identify drift was done by monitoring the sensors for an extended period of time (Figure 10). Measurements were taken every two hours, for a total of 34 measurement sets (during a 68-hour period). Two FOSG exhibit good stability, remaining within 0.5 μstrain. One FO sensor (Fiber 2) follows closely the temperature curves, and drifts further at the end. Foil sensors change by as much as 1.5 μstrain. Drift was probably not associated only to temperature variations (less than 1°C), but other factors such as the stability of signal conditioning electronics.

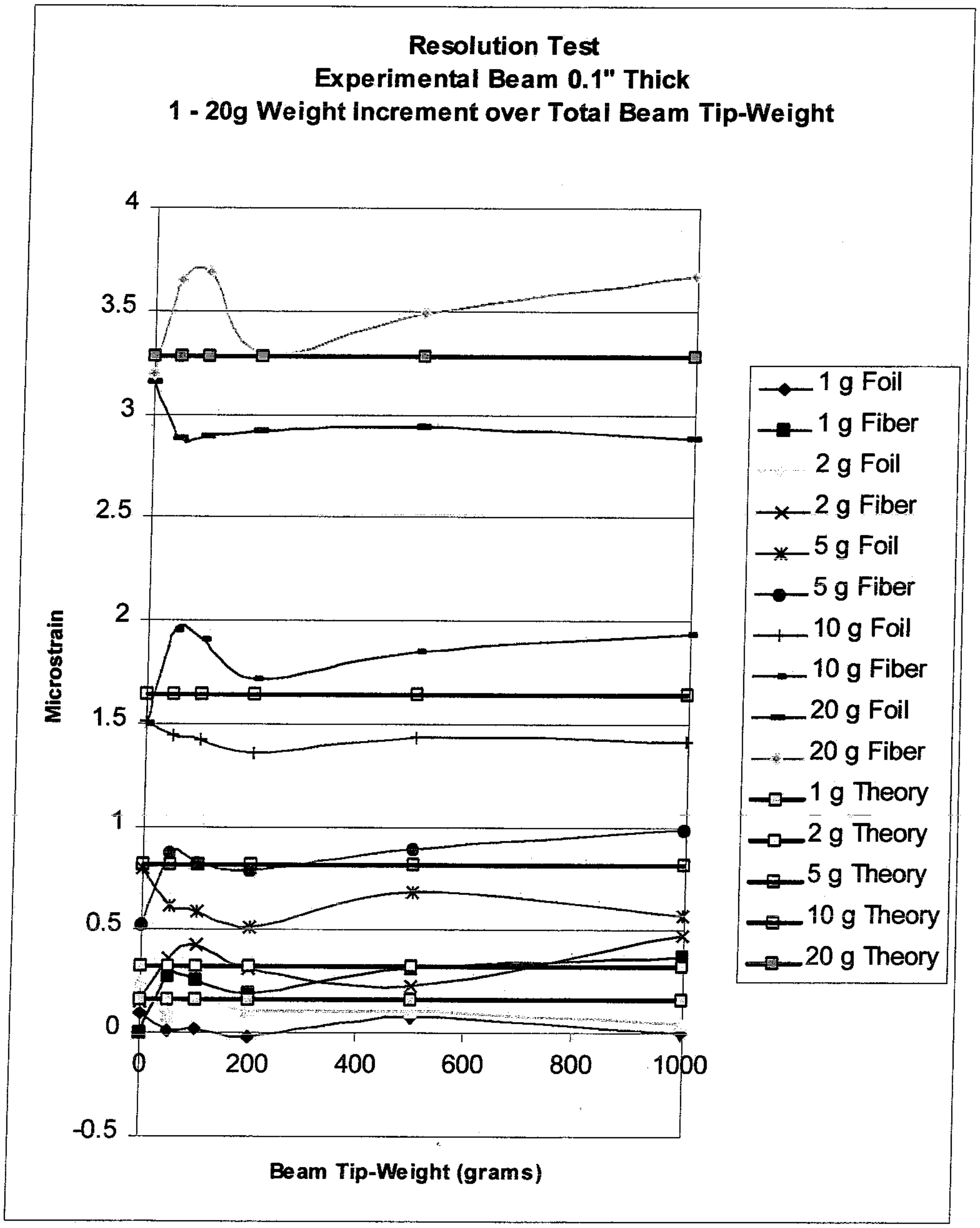

Figure 9 Resolution experiment with Beam 1.

A second experiment using the weighs was done to further investigate precision and linearity (Figure 11). The experiment consisted of 2 load-unload cycles with the weights. Linearity and precision are very good. Fiber 2 exhibits the largest discrepancy of about 1.2 μstrain at around 10 μstrain of total deformation. All other sensors have discrepancies of less than 0.5 μstrain.

Since Fiber 1 exhibited values farther from to those of the foil sensors, it was removed and replaced by another sensor Fiber 1R. Later, a third fiber was added to Beam 2, Fiber 3, to further investigate variations from one FOSG to another. Measurements show that these variations range from 2.4% to 11.9%.

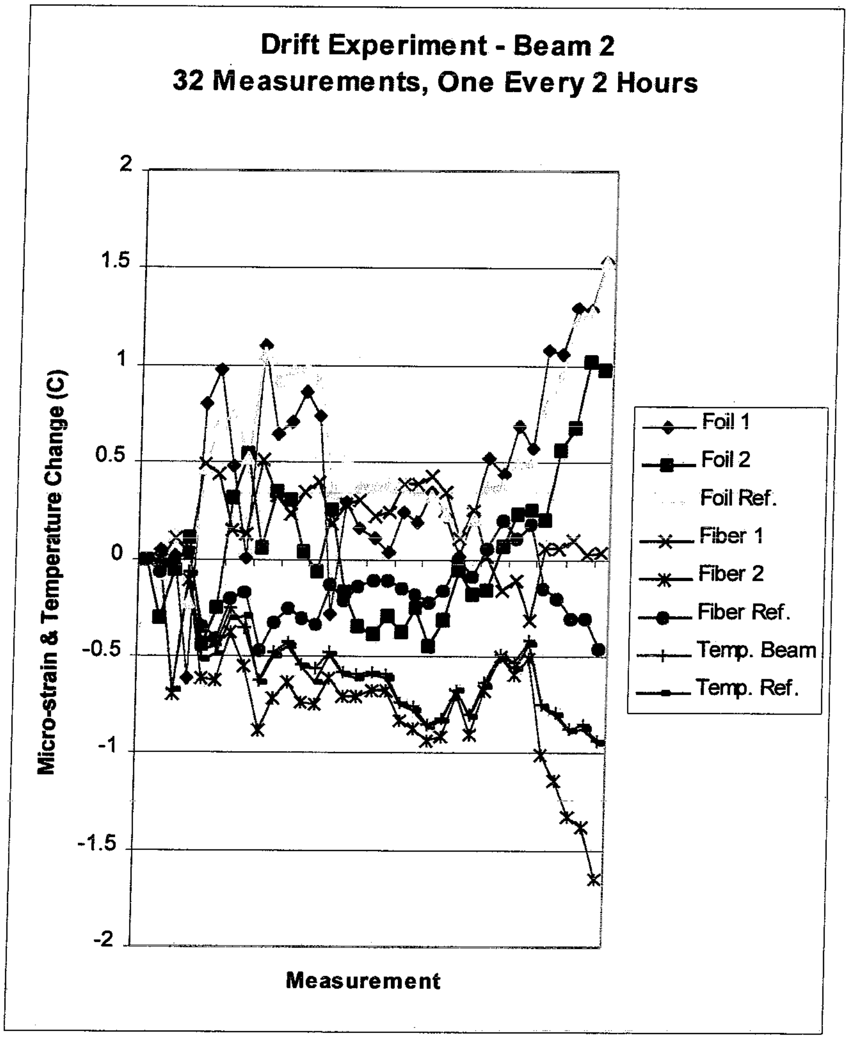

Figure 10 Drift experiment with Beam 2.

A temperature experiment was performed by heating the beams using a light bulb. Temperature was increased and measurements were taken every two hours. The test and reference beams were placed in an enclosure and the temperature was changed by controlling the light intensity. Foil sensors exhibit the expected non-linear behavior (Figure 12). Two of the three FOSG are not significantly affected by temperature variations (Figure 13). Fiber 1 shows insufficient temperature compensation. Using the reference sensor to compensate for temperature works well for the foil sensors (Figure 14).

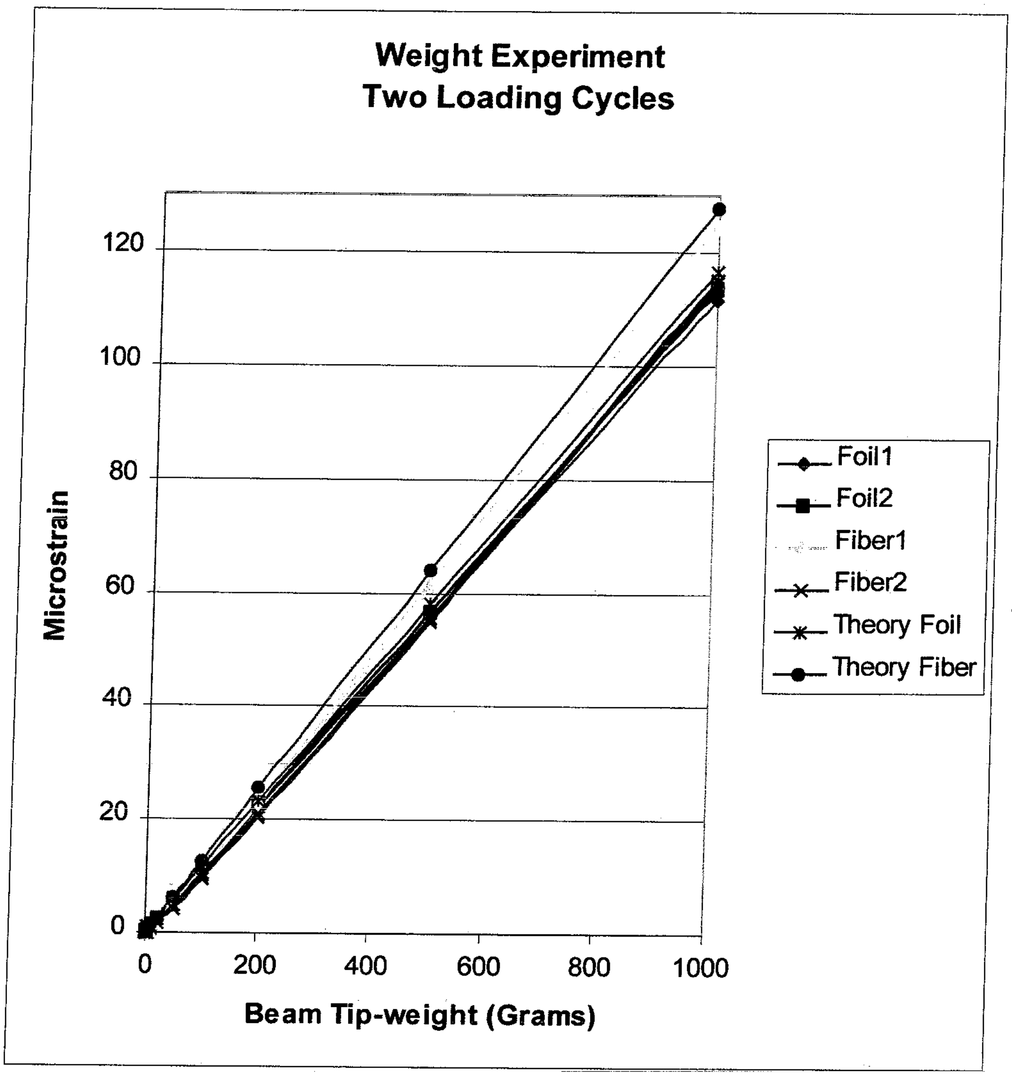

Figure 11. Linearity and precision experiment with Beam 2.

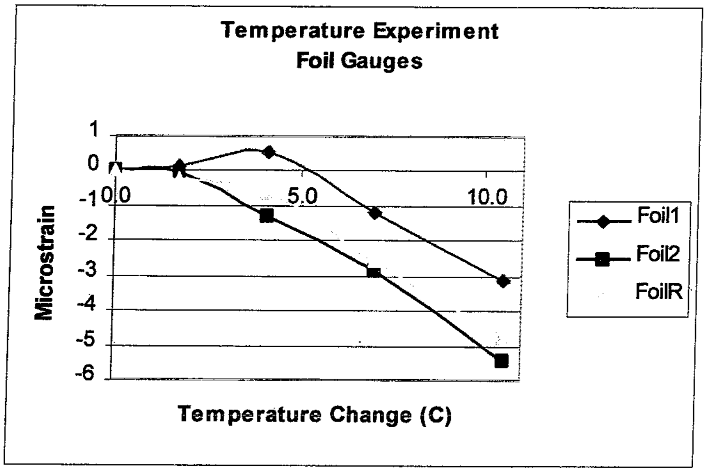

Figure 12 Uncompensated foil gages performance with increasing temperature from ambient.

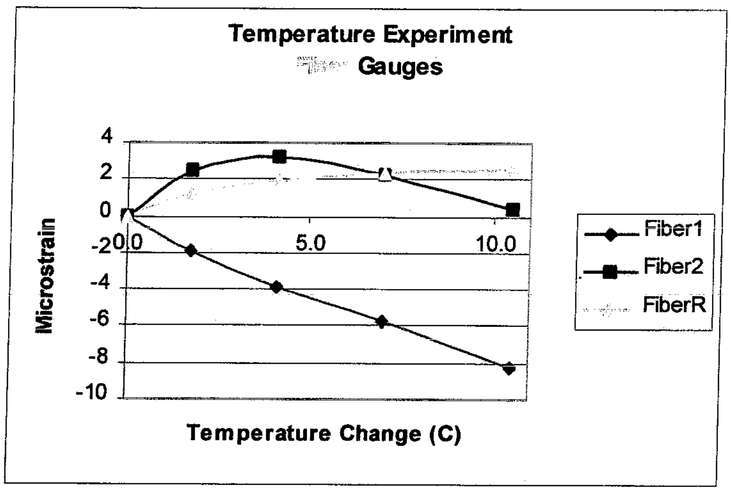

Figure 13. FOSG performance with increasing temperature from ambient.

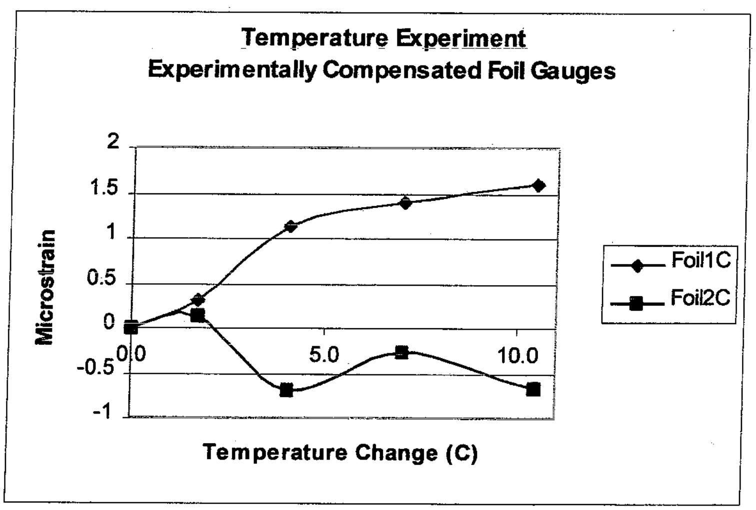

Figure 14. Compensated foil gages performance with increasing temperature from ambient

Error Analysis

Alignment and location of sensors were considered as possible causes of experimental error. However, it was determined that the measurements were not very sensitive to these errors. In order to account for the observed variation in values from one FOSG to another, a location error along the beam of at least ¼" would be needed. Experimental sensor location was at least ten times better than that value. Alignment errors of the order of 5 degrees cause only 0.4% strain error, and again, sensors were aligned at least ten times better than that value. Other errors caused by the electronic processing systems were minimized by ensuring appropriate warm up periods and zeroing of biases at the beginning of each experiment.

Cost Considerations

A traditional foil sensor and conditioning unit cost approximately $3,000. This does not include costs of data acquisition and analysis. A data acquisition system may add another $625 (Assuming a $5,000 data acquisition system with 8 channels). The cost of a FOSG and signal conditioner from FISO Technologies [7] comes to approximately $3,850, plus approximately $400 for data acquisition). Luna Innovations [8], using probably a somewhat different technology charge approximately $6,900. Hence, at least for one brand of FOSG, costs are comparable to those of traditional foil sensors.

Conclusions and Recommendations

Table I summarizes experimental data and other considerations. Experimental results are limited to strain measurements from zero to 180 μstrain, and temperature variations of approximately 11 °C above ambient. Both types of sensors have equivalent linearity and precision at quasi-constant temperature conditions (ambient). Cyclic strains show a variation of less than 0.5 μstrain on all sensors, except for one FOSG that exhibited a 1.2 μstrain variation. Both technologies have equivalent resolution of approximately 0.8 μstrain, independent of the total level of strain. For small temperature variations (less than 1°C), both technologies exhibit small drifts (less than 1.5 μstrain). The FOSG were temperature compensated, but one exhibited deficient compensation. It may be that the metallic compensating fiber used did not have the same coefficient of thermal expansion of carbon steel. Foil gages behaved predictably nonlinear with temperature variations. Finally, measurement variations from one FOSG to another were significant, from 2.4% to 11.9 %. Therefore, individual calibration of FOSG is necessary to obtain accurate absolute measurements.

Table I. Summary of Experimental Data and Performance Considerations

Sensor Type	Variation from sensor to sensor (%)	Precision (μstrain)	Resolution (μstrain)	Temperature Induced Maximum Error (μstrain)	Drift Maximum Error (μstrain)	Corrosion Resistance	Complexity of Operation	Noise Immunity
FOSG	2.4-11.9	0.5, 1.2	0.8	-2.2 & -10.8	1.5	High	Low	High
Foil	1.8	0.5	0.8	0.7 & 1.6	1.5	Low	High	Low
Comments	0-180 μstrain range	0-180 μstrain range	0-180 μstrain range	For 11 °C variation. Two FOSG and two foil gages	Over 68 hours and less than 1°C variation		FOSG signal processors were easier to operate.	

FOSG are "better" than foil sensors in that they exhibit a linear behavior with temperature. Although compensated gages were used in the experiments, it may be best to use uncompensated units to improve calibration/accuracy. Compensated FOSG have additional sources for errors as they have to be fitted with a metallic fiber of very accurate dimensions and coefficient of thermal expansion. FOSG are also "better" because of their inherent properties that include high immunity to RFI and corrosion, spark-less operation, robust signal conditioning with low probability of making mistakes and easy integration into a data acquisition system, and their signals can be transported long distances (miles) without deterioration. FOSG were also easier to operate (lower Complexity of Operation, in Table I). The processing software and electronics were easy to use and provided diagnostics that ensured high integrity of the data. The signal processing (hardware) for the foil sensors required more attention.

FOSG are "worse" than foil sensors in that variation of the sensor gage factor from one unit to another is much larger. Therefore, each unit must be individually calibrated if one needs accurate absolute measurements. In the LOX tank application, FOSG can be easily calibrated by recording two strain values, when it is empty and full (or any set of two distinct known levels). If the FOSG is encapsulated as a component of a sensor, then it can be calibrated in the laboratory. Foil gages technical experts from Measurements Group, Inc. [9] indicated that accuracy better than 1% is attainable in laboratory environments and around 5% in field installations.

Over a small temperature range about ambient, FOSG are "equivalent" to foil sensors in linearity, precision, and resolution.

Calculations to determine predicted deformations of the LOX-tank support structure are attached in the appendix.

Acknowledgements

The authors wish to thank Mr. Lester Langford for his assistance in acquiring and setting up the sensors and instrumentation (hardware and software) that made possible this work. We are also thankful to Lester for his valuable recommendations and suggestions on matters related to sensors and instrumentation. We thank, as well, Mr. Charles Thurman for his support and assistance concerning circuit theory.

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[6] National Instruments, Austin, Texas, USA.

[7] FISO Technologies, Inc., Sainte-Foy (Quebec) Canada G1N-4N6.

[8] Luna Innovations, Blacksburg, VA, USA.

[9] Measurement Group, Inc., Raleigh, NC, USA.

Appendix

Application of the FOSG to measure the level of LOX Tank V-14A01-LO considers placement of the sensors in three support beams. As the tank is filled from empty to full, the total strain in each leg varies from 0 to approximately 11 μstrain. Assuming a 1 μstrain resolution, each FOSG would provide 11 discrete height measurements. Adding measurements from a number "n" of FOSG would increase the resolution by a factor of "n." If n=3, then 33 discrete height measurements are possible. Given the spherical geometry of the tank, the largest deformation is produced for height increments when the tank is half-full, and the smallest deformation when it is almost empty or almost full. Assuming 33 discrete height increments, the volume measurement resolution when the tank is half-full is 136 gallons and 42 gallons when it is 80% full. Calculations are included in the following pages.

Related Publication

NASA/TP-2000-210639

Characteristics of Extrinsic Fabry-Perot Interferometric (EFPI) Fiber-Optic Strain Gages

David A. Hare and Thomas C. Moore, Sr.
Langley Research Center, Hampton, Virginia

December 2000

Abstract

The focus of this paper is a comparison of the strain-measuring characteristics of one type of commercially available fiber-optic strain sensor with the performance of conventional resistance strain gages. Fabry-Perot type fiber-optic strain sensors were selected for this testing program. Comparative testing is emphasized and includes load testing at room temperature with apparent strain characterization cryogenically and at elevated temperatures. The absolute accuracy of either of these types of strain gages is not addressed.

Introduction

Langley Research Center (LaRC) uses strain gages in many varied and challenging test environments. As testing scenarios become more demanding, not only at Langley but at other testing centers, there is the realization that current strain gage technology does not and cannot provide a reasonable means for measuring strain when certain testing requirements are encountered. A relatively new type of strain sensor, the "fiber-optic" (F-O) strain gage, offers the promise of making strain measurements where resistance-type strain gages fail to provide the desired features. Manufacturers of F-O strain gages state the following advantages when using their strain sensor: immunity to electromagnetic interference, immunity to leakage-to-ground problems, and no inaccuracies associated with long, multiple, signal lead requirements. The fiber-optic strain gage's lower mass provides a significant weight savings. Also, this reduced mass in the F-O gage minimizes reinforcing effects that conventional strain gages can induce in a test article. Most of these stated advantages with the F-O gages are the typical shortcomings of the resistance gages, especially where flight testing or "testing in the field" is involved.

There are several types of fiber-optic strain gages, two of which comprise the majority of commercially available strain sensors. The most popular manufacturing method produces the Fabry-Perot strain sensor with the second most popular type being the Bragg-grating strain sensor. This paper presents a comparison of performance characteristics between the Fabry-Perot type fiber-optic strain gage with a widely used conventional resistance strain gage. As described by Tran, the Fabry-Perot type of sensor uses a phase difference or "shift" between reference and sensing reflections of the fibers for making strain measurements [1]. This phase shift described by Tran and others is then used to calculate strain. In the world of structural and/or materials testing, the means to generate real-time data in engineering terms is a practical necessity. This "necessity" is addressed by Tran, et al, in another paper in which a means of measuring absolute strain in real time is described [2]. In this paper, comparative data with a conventional resistance strain measurement system and a dedicated "strain measuring system" for a Fabry-Perot type strain sensor (with its fiber-optic gages inclusive) will be presented. The ability of the F-O strain measuring system and its gages to measure strains comparative to resistance gages will be discussed.

A brief description of this type of F-O gage is provided in the paper. Comparative testing includes load testing at room temperature with apparent strain characterizations cryogenically and at elevated temperatures. Although some load tests are performed with the fiber-optic gages in compression, the primary configuration is in tension. Test results are presented as phase 1 testing and phase 2 testing. Presenting test results in two phases is due to the manufacturer's change in the manufacturing process as the first group of gages was being tested. Note that the manufacturer of the gages offered an improved F-O sensor as the first group of gages was being evaluated. It was decided to procure these "improved" gages and test them as part of this effort. Thus, data from phase 1 testing are generated from the first

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13. ABSTRACT (*Maximum 200 words*)

For years, resistance based strain sensors have been used for the measurement of strain. The resistance-type strain gage provides a very reliable and accurate measurement of strain, but as with any instrument it has its limitations. Extrinsic Fabry-Perot Interferometric (EFPI) fiber-optic strain sensors are now commercially available from several manufacturers. Fiber-optic strain gages have stated advantages over resistance based strain gages, including immunity to electromagnetic interference (EMI) and leakage to ground. This paper presents a limited performance comparison between the (Fabry-Perot type) fiber-optic strain gage and the traditional resistance strain gage. The evaluation was limited to load testing at room temperature and apparent strain characterization cryogenically and at elevated temperatures. The fiber-optic strain gage evaluation was limited to gages produced by one manufacturer.

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